Charge to the Participants

Provide roadmap for APS on future of x-ray imaging

- Identify the grand challenge Scientific/Engineering problems in various disciplines that synchrotron x-ray imaging should address - now *and* 5-10 years from now.
- Identify the challenges and requirements needed to successfully answer these questions
  - ➢ New instrumentation and techniques needed
  - ➢ Need for dedicated beamlines and instrumentation
- Identify short and long-term R&D needed to achieve above - such as detectors, tomographic data mining, optics and sample environment

Workshop Focus

- Full field hard (> 5 keV) x-ray imaging
- Scientific applications - present & potential
- Cover broad and diverse disciplines

LIFE SCIENCE CONTRIBUTORS

- Erik Ritman, Mayo Clinic, Rochester.
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- Kathleen Donohue, Organismal and Evolutionary Biology, Harvard Univ.
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- Beth Brainerd, Biology Dept., Univ of Massachusetts.
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- Charles Boyce, Dept of Geophysical Sciences, Univ of Chicago.
- Steve Cook, Dept of Biology, Univ of Utah.
- Dean Chapman, Anatomy & Cell Biology, Univ of Saskatchewan.

This group is mostly interested in “macro” samples.

For this group, X-ray imaging offers:

- 3-D imaging
- Micron to sub-micron resolution
- Can look at thick macroscopic samples eg, a mouse.
- Real time capability
- High sensitivity

These are capabilities that are not available by other techniques.

QuickTime™ and a
Sorenson Video 3 decompressor
are needed to see this picture.

LIFE SCIENCE - GRAND CHALLENGES

- Digital morphology library for small organisms
- Image gene expression for discovery of gene function
- Discover and describe early life on earth (micro-fossils) 0.6-3.6 x 10^9 yrs and extra-terrestrial life
- Real time imaging of physiological processes on a small scale (functional imaging)
- Comparative characterization of the evolutionary transitions that underlie the diversity of life

THE ABILITY TO LOOK INSIDE SMALL ORGANISMS WITH MICRON AND SUB-MICRON RESOLUTIONS AND IN PARTICULAR, IN REAL-TIME, MIGHT BE SIMILAR IN IMPACT AS THE INVENTION OF THE OPTICAL MICROSCOPE OR THE ELECTRON MICROSCOPE FOR THE LIFE SCIENCES

Digital morphology library for small organisms

• This will be a MAJOR INVALUABLE RESOURCE equivalent to the National Library of Medicine's 'Visible Human Project' or the NSF's 'Digital Morphology Project' for biologists.

- Map 3-D branching structures, eg., plant root hairs, insect tracheal system, neural networks, micro-circulation.
- Fills a dimensional gap (1-10 micron resolution)

- Beam size of centimeter scale
- High throughput
- Environmental control
- Contrast agents
- Data storage/analysis/distribution

Image gene expression for discovery of gene function

- Think of the explosion of discoveries due to luciferase-tagged genes. Yet, its utility is limited to small / transparent organisms where the visible green light can be detected but not well quantified. If the x-ray equivalent of this is possible, it will be of INCREDIBLE IMPACT with enormous life-enhancing and socio-economic benefits.

  - When and where a gene is expressed, eg., during embryonic development and aging
  - Characterize environmental dependence of gene expression eg., pesticides
  - Evaluation of large mammal intact tissue biopsies

- X-ray equivalent of fluorescent gene tags
- Sample environment
- Beam size in centimeter scale
- High sensitivity - phase techniques
- Possibly coupled with other techniques

Discover and describe early life on earth (micro-fossils) 0.6-3.6 x 10^9 yrs and extra-terrestrial life

- This will open a NEW FRONTIER in paleontology.
- It will REVOLUTIONIZE the way paleontologists look for and at fossils.

  - Organisms that live in extreme environments
  - Screening specimens for rare imbedded fossils
  - Non-destructive visualization of anatomy of fossil soft-tissues

- High throughput
- Sensitivity - phase techniques
- Elemental and chemical maps (3-D EXAFS)
- Contamination prevention
- Contrast agents
- Zooming capability

Real time imaging of physiological processes on a small scale (functional imaging)

- This technique opens a TOTALLY NEW WINDOW for physiologists.
- The results will likely lead to a REWRITE of TEXTBOOKS.

- Chemical, mechanical and transport processes eg., insect respiration, digestion, blood flow, feeding, reproduction

- Multi-view imaging or real-time tomography
- Zooming capability
- High speed imaging
- Simultaneous physiological measurements
- Environmental control
- Sensitivity - phase contrast
- Contrast agents and markers
- Animal care facility

Comparative characterization of the evolutionary transitions that underlie the diversity of life

- 'Nothing in biology makes sense except in light of evolution' *Dobzhansky*
- Opens up entire new avenues to study evolution

- Comparing large numbers of samples using the above approaches, one can infer evolutionary transitions and mechanisms for diversification especially in the presence of rapidly changing environments.
- Eg., tracking evolution of novel fruit morphology as a function of geographic distribution
- Eg., Is tracheal pumping related to evolution of flight in insects?
- Eg., How does the lock and key mechanism of insect genitalia contribute to rapid speciation (relevant to agriculture)

- High throughput
- Zooming capability
- High speed imaging
- Simultaneous physiological measurements

- Environmental control
- Sensitivity - phase contrast
- Contrast agents and markers
- Animal care facility

APS is far behind in imaging compared to ESRF & Spring-8 where there are dedicated long (150 m & 250 m) imaging beamlines.

- NO beamline at the APS has a clean beam.
- High quality quantitative phase retrieval techniques (eg, holotomography (Cloetens, ESRF)) which are essential for imaging soft tissue CANNOT be done currently at the APS.
- The lack of a LONG beamline limits the beam coherence which limits the sensitivity & resolution achievable with phase techniques. Assuming 10 m sample-detector, geometric blurring of source at APS at 60 m is ~ 2 micron vertically.
- The lack of a LONG ID beamline limits the size of beams available. An ID beamline is needed for intensity (eg., real time imaging) & high throughput.

The APS needs a DEDICATED IMAGING LONG BEAMLINE.

NORTHWESTERN
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S.R. Stock
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and a cast of several dozen

X-ray Imaging Opportunities: Materials Science & Complex Systems

ADVANCED
PHOTON
SOURCE

Provide roadmap for APS on future of x-ray imaging

- Materials and complex systems problems now *and* 5-10 years from now.
- Impact: Results that change how others do their science.

  Results that have major economic impact.

  Results that re-write textbooks.

- What grand challenges?
- What do they require?

Materials Science – Complex Systems

- Macroscopic properties of bulk “real world” materials depend upon a hierarchy of structural length scales (nm to cm).
- Multiple observations on the interior of the same sample are essential.

Some Grand Challenges

(selected from applications important to a diverse community)

- Understanding materials deformation (metals deformation, development of texture during processing) and fracture (crack initiation, opening and closing).
- Understanding failure mechanisms within engineered structures.
- Understanding dynamic processes, particularly in extreme environments.

Materials deformation / fracture: Relationship between microstructure and response

- Current models are woefully inadequate to predict materials deformation typically encountered during service or processing, largely because adequate data on the hierarchy of deformation scales and their interactions do not exist.

- Crack initiation and propagation: Similar limitations.

- Providing the necessary information requires ~100 nm beam diameters for 3D (spatial) diffraction quantification of the altering materials response as a function of deformation, etc. combined with imaging (of small ~50 nm precipitates).

- Example of Impact: Metal forming for cars, >$20 billion/yr industry. Poor understanding of deformation leads to ~12 iterations in stamping die design for mild steel. For newer generation sheet materials high strength steels or Al >> 12 iterations.

Failure mechanisms:
a. Multilayer semiconductor structures
b. Environmental attack of cement

- Complex layered structures at scales below 1 μm. Implies probe diameter, spatial resolution in imaging ~ 100 nm.
- Thermal expansion mismatches plus gale-force electron winds.

•Failures buried and cannot be disinterred without destroying the information of interest. Involves a complex combination of stresses, strains, partial decohesion of thin films, transported materials.

•Employ diffraction imaging (topography via rastered beam < 100 nm) plus other point x-ray probes on the same scale.

•ULSI manufacturing requirements dictate understanding subtle effects separating marginal, failure-prone processes from acceptable ones.

Failure mechanisms:

a. Multilayer semiconductor structures

b. Environmental attack of cement

- Extending lifetimes of cement-based structures in normal as well as aggressive environments is a major challenge.
- Manufacture of cement is very energy intensive and contributes large amounts of greenhouse gases.

- Cement is: hydrated, drying changes its properties.
  heterogeneous at multiple length scales (nm to mm).

- Cement: Paradigm for various porous / microporous materials (including oil containing rocks).

- Environmental attack (a major concern) proceeds by ingress of sulfate or other ions via capillary flow.

- Understanding damage: Repeated imaging of the same sample. Dimensions of channels and early reaction products requires imaging with 100 nm spatial resolution plus use of additional techniques probing the same length scale.

Dynamic processes in extreme environments

- Plunger dynamics in fuel sprays (μs image acquisition now is adequate), working through mm-cm steel.
- Droplet formation in fuel sprays (need ps exposures instead of μs). Phase contrast is important. This requires improved
  - Microfocus optics
  - Detector development
- This should lead to rational design of combustion processes.
- Paradigm for many fluid dynamics problems.

- Related problem: Inkjet printing processes for rapid prototyping
  - Very small jets, extremely high resolution required.
  - Extremely high dimensional tolerances needed, not only in deposition but also in subsequent processing.

What we need

- High Definition **implies long beam line**
  - Large field of view +
  - High spatial resolution +
  - High sensitivity
- Clean optics, very stable beams
- Detectors improved plus zooming capability
- Friendly analysis tools, local analysis team
- In situ/environment + multi-mode/indexing
- For certain applications, high throughput/data collection rates.

Some X-ray imaging techniques

- Phase or absorption microtomography.
- Phase or absorption microradiography.
- Diffraction imaging.
- **None of the techniques has required resolution for the next generation problems outlined above**.

Specifically

- High Definition **implies long beam line** (~200 m)
  - Large field of view + several cm
  - High spatial resolution + 100 nm
  - High sensitivity $\Delta\rho/\rho << 1\%$
- Clean optics, very stable beams
- Detectors improved plus zooming capability
- Local analysis team, friendly analysis tools
- In situ/environment + multi-mode/indexing
- Tinker-toy x-ray imaging (standard set-up which can be implemented in many places)

A suggestion for the future:

The possibility of imaging nanoscale non-crystalline objects (isolated biological macromolecules, virus particles, etc.) with nanometer resolution via lens-less coherent diffraction imaging.

Why? Some biological macromolecules have defied attempts to crystallize them.

Finally,